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ELECTROSTATIC ACCELERATION OF NEUTRAL PLASMAS – MOMENTUM TRANSFER THROUGH MAGNETIC FIELDS

by
G. S. JANES
and
T. WILSON

AVCO-EVERETT RESEARCH LABORATORY
EVERETT, MASSACHUSETTS

Electrostatic Acceleration of Neutral Plasmas -

Momentum Transfer through Magnetic Fields*

by

G.S. Janes, J. Dotson, and T. Wilson

Avco-Everett Research Laboratory, Everett, Massachusetts

ABSTRACT

Electrostatic plasma accelerators which avoid the space charge limitations of conventional ion rockets are described. Additional advantages for these devices include moderate requirements on magnetic field strength, and on power level. In cylindrical and annular geometries, neutral plasmas can exhibit axial acceleration under the influence of externally applied axial electrostatic fields in the presence of radial magnetic fields. Ions will accelerate freely in the presence of such an axial electric field if both the ion gyro radius and the ion mean free path are large relative to the apparatus size. The axial drift of electrons, however, will be strongly inhibited by the radial magnetic field if the electron gyro radius is small relative to both the apparatus size and to the electron mean free path. The resulting circumferential drift of electrons constitutes an electric current which in turn produces a magnetic reaction force on the external field coils. The electric field is impressed upon the plasma by means of an upstream anode and a downstream cathode. This cathode serves as a source of electrons for space charge neutralization of the exit plasma beam. A critical engineering question concerns the effectiveness of the radial magnetic field in inhibiting the upstream diffusion of electrons. This diffusion is an energy loss mechanism. Both classical and anomalous (Bohm type) electron diffusion models are considered. Experiments are described which substantiate the existence of the here described mechanism for momentum transfer to neutral plasmas. The experiments are in approximate agreement with the anomalous (Bohm type) diffusion model and are in clear disagreement with the classical diffusion model. The engineering significance of this result and possible approaches for dealing with it are considered.

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I. Introduction

This paper discusses the electrostatic acceleration of electrically neutral plasmas* under conditions where the energy input is produced by an applied electrostatic field parallel to the direction of plasma acceleration, while the momentum input is produced by an applied magnetic field with components perpendicular to the direction of plasma acceleration. Electrostatic accelerators which employ this mechanism are not subject to the space charge limitations which restrict the thrust density of conventional ion rockets. This acceleration mechanism can occur in a domain which we have chosen to call the Electric, Magnetic, or more briefly, E. M.[1] region of plasma physics.** In this domain both the ion gyro radius and the electron mean free path between collisions are large relative to the apparatus size, while the electron gyro radius and the Debye shielding distance are still relatively small. Under these conditions, the motion of electrons perpendicular to magnetic field lines is inhibited, thereby permitting the plasma to sustain an electric field which is associated with the forces necessary to accelerate the ions. For this phenomenon to occur, it is essential that the charged particle mean free paths be very long in order that electron currents in the direction of the applied electrostatic field may be reduced by $\omega_e \tau_e$ effects. Thus, there is no effective mechanism for accelerating neutral atoms, and a high degree of ionization is essential. It is in this sense that the experiments described here differ from experiments such as the magnetic annular arc.[2-4]

Experimental work (see Figs. 1 & 2) on E. M. region D. C. plasma accelerators has been undertaken at the Avco-Everett Research Laboratory[5-8] and at the United Aircraft Corporation Research Laboratory.[9-10] At Avco, this concept had its origin in experiments performed with a low density electrodeless steady state traveling wave cusp accelerator.[6-8] Figure 3 is a schematic diagram of this accelerator. Pertinent physical parameters are listed in the accompanying table. This electrodeless accelerator operates in the E. M. region. Therefore, it was not possible to control the ion motions directly with magnetic fields. However, the small magnitude of the Debye length relative to the apparatus size imposed a requirement that the aggregate ion and electron velocities be essentially equal. Thus, forces which were transmitted to the electrons by the magnetic fields could be retransmitted to the ions indirectly by electrostatic fields arising as a result of slight perturbations in the local charge neutrality.

Detailed experimental studies of this device included measurements of external quantities such as mass flow rate, R. F. power absorption in the plasma, local and integrated wall heat transfer rates, and integrated axial voltage gradients. Internal studies included Langmuir probe measurements of

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* Plasmas wherein the charge particle densities of ions and electrons are essentially equal.

** In Ref. 5 it is shown that steady state operation of high velocity magnetically contained plasma accelerators at magnetic field energy densities comparable with the plasma energy densities ($\beta \approx 1$), moderate power levels (< 50 kw), and sizes consistent with the use of magnetic containment leads almost inevitably to these E. M. conditions.

the ion flux distributions, of the plasma potential distributions, and of the electron temperatures. Probe measurements were also made of the magnetic field perturbations and of the energy density in the flow. Distributions of the local momentum flow (ρv^2) were measured with a small quartz thrust plate of known area. This plate was mounted on a long shielded stem which in turn was mounted on top of a mechanical scale. The momentum flow distributions were integrated in order to yield the total thrust. On the basis of measurements of thrust and mass flow rate, specific impulses of 2600 seconds were computed. This corresponds to 2/3 of the phase velocity of the traveling cusps. These experimental studies indicated that the E. M. region acceleration mechanism was remarkably effective; the most striking feature being the appearance of strong electrostatic fields which were closely correlated with the ion accelerations (see Figs. 4 & 5).

The observation that the traveling wave mode was characterized by a strong axial D. C. electric field in the absence of any external voltage source led to the suggestion that an externally applied axial D. C. electric field might actually improve the performance. Experiments[7] using such an axially connected external voltage source indicated that, by this method, the mean plasma velocity could be approximately doubled.

A model was proposed in which the drift of electrons between adjacent cusps was inhibited by intervening regions containing purely radial magnetic fields while the ions were essentially free to accelerate under the influence of the local electric fields. This interpretation was further substantiated by the observation that it was not possible to accelerate, or even to couple energy into, the plasma utilizing the traveling wave mirror configuration. This would be expected because of the presence of continuous magnetic field lines which permit the secondary flow of electrons counter to the direction of acceleration, thereby short circuiting the axial electrostatic voltage gradients.

In regions of strong radial magnetic fields, the reverse leakage of electrons should be calculable on the basis of the classical collision dominated diffusion theory. It was also recognized, however, that additional electron leakage would occur because of the absence of any magnetic field along the singularity occurring at the central axis. In the traveling wave accelerator this mechanism was not considered to be too serious since it provided a source of high energy electrons which were very necessary for ionization.

II. Elementary Theory

A) Momentum Conservation - Referring to Fig. 6, we consider the aggregate motion of electrons and ions in the presence of an axial electric field and a (perpendicular) radial magnetic field. We define our symbols as follows:

e	$\equiv$	charge on the electron
m_e	$\equiv$	electron mass
m_I	$\equiv$	ion mass

n_e	$\equiv$	electron density
n_I	$\equiv$	ion density
E_x	$\equiv$	axial electric field
B_r	$\equiv$	radial magnetic field (perpendicular to E_x)
j_e	$\equiv$	$n_e v_e e$ = electron current density
j_i	$\equiv$	$n_i v_i e$ = ion current density
τ_e	$\equiv$	mean collision time for electrons
ω_e	$\equiv$	$(eB)/(m_e)$ = electron cyclotron frequency
r_e	$\equiv$	electron gyro radius
r_I	$\equiv$	ion gyro radius
h	$\equiv$	Debye shielding distance
λ_e	$\equiv$	electron mean free path
ℓ	$\equiv$	channel length
R	$\equiv$	channel aperture
c_e	$\equiv$	electron thermal velocity
kT_e	$\equiv$	electron thermal energy (ev)
V	$\equiv$	$\int_o^{\ell} E\,dx$ = integrated axial voltage gradient
η	$\equiv$	$(kT_e)/(eV)$ = ratio of electron temperature to maximum ion energy
σ_o	$\equiv$	$(n_e e^2 \tau_e)/(m_e)$ = scaler (Spitzer) electrical conductivity
ϕ	$\equiv$	$(r_I)/(\ell)$
$\dot{m}$	$\equiv$	mass flow rate
I_o	$\equiv$	$\dot{m}\,(e/m_I)$
P_I	$\equiv$	total power input to directed ion energy
P_e	$\equiv$	total power input to electron heating
ϵ_o	$\equiv$	dielectric constant of free space
β	$\equiv$	$(n_e kT_e)/\left(\frac{B^2}{8\pi}\right)$

For E. M. region conditions the ions are free to accelerate in the axial direction under the influence of the local electric field, but the electrons can only move in the axial direction by undergoing collisions. Instead, the primary electron motion will be a drift in the $\vec{E} \times \vec{B}$ direction with velocity E/B. This represents an electrical current of magnitude $j_\theta = n_e e\,(E_x)/(B_r)$.* This current produces a net force per unit volume F_v given by Eq. (1).

$$F_v = j_\theta B_r = n_e e E_x \tag{1}$$

By remembering that $h \ll R$, we note that:

$$n_e = n_I \tag{2}$$

hence

$$F_v = j_\theta B_r = n_I e E_x \tag{3}$$

Equation (3) states that the net electrostatic force per unit volume on the ions is identically equal to the net magnetic force per unit volume on the electrons; these forces being transferred between electrons and ion by slight perturbations in the local electrostatic charge neutrality. The circumferential circulation of electrons constitutes an electrical current which in turn transfers these forces to the coils.

B) Space Charge Limitations - Accelerators of this type do not have the usual space charge limitations. For the simple one dimensional model of an electrostatic plasma accelerator, elementary electromagnetic field theory indicates that Eq. (4) must be satisfied.

$$\frac{e}{\epsilon_0} \int_0^{l_n} (n_I - n_e)\, dx \leq E_{x\,MAX} \tag{4}$$

If Eq. (4) is not satisfied, the externally applied electrical field will be destroyed by the intervening charge distributions. In conventional ion rockets, the requirement that $n_e = 0$ leads to the familiar Childs law limitation on

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* This result can also be derived from the tensor electrical conductivity equations.

current. This imposes a practical upper limit of about 400 dynes/cm^2 on the specific thrust per unit area. This space charge restriction does not apply to the devices under consideration here since $n_I = n_e$ everywhere within the plasma except at the sheaths.

C) Electron Leakage Currents - Classical Diffusion Case - The power input through ion currents, $P_I = \int j_{Ix} E_x d\,Vol$, is deposited in directed energy, but the energy input through electron currents, $P_e = \int j_{ex} E_x d\,Vol$, is deposited in heat and ionization. Thus, the ratio j_{ex}/j_{Ix} represents an estimate of the fractional losses to heat and ionization.

With certain simplifying assumptions, it is possible to construct a zero order theoretical model for predicting this ratio.

Because of symmetry, the circumferential electric field must vanish. If the electron drifts follow the classical $1/B^2$ diffusion law,[11-13] current can be expressed by use of the familiar tensor conductivity relation.

$$j_{ex} = \frac{\sigma_o E_x}{1 + (\omega_e \tau_e)^2} \approx \frac{n_e e^2 \tau_e E_x}{m_e (\omega_e \tau_e)^2} \tag{5}$$

Equation (5) expresses this classical relation for the diffusion of electrons across a magnetic field. The unit term has been disregarded relative to $(\omega_e \tau_e)^2$. Since $R_i > \ell$, the ions are free to accelerate in the axial direction under the influence of local electric fields. Hence, the ion current density can be written as:

$$j_{Ix} = e n_I V_{Ix} = e n_I \sqrt{\frac{e \int_0^x E_x dx}{1/2\, m_{Ix}}} \tag{6}$$

Remembering that $n_e = n_I$ and substituting V for $\int_0^x E_x dx$ and V/ℓ for E, we can write an order of magnitude equation.

$$j_{ex}/j_{Ix} \approx \frac{e V \tau_e}{m_e (\omega_e \tau_e)^2 \ell \sqrt{eV/m_I}} \tag{7}$$

Noting that $\omega_I = \omega_e \; m_e/m_I$, that $v_I/\omega_I = r_I$, and that $\omega_e\tau_e = \lambda_e/r_e$, Eq. (7) can be written in simplified form.

$$j_{ex}/j_{Ix} \approx \frac{\sqrt{eV/m_I}}{\omega_I(\omega_e\tau_e)\ell} = \left(\frac{r_I}{\ell}\right)\left(\frac{r_e}{\ell}\right)\left(\frac{\ell}{\lambda_e}\right) \tag{8}$$

Taking account of the fact that $r_e/r_I = (m_e/m_I)^{1/2}\,\eta^{1/2}$, we obtain Eq. (9).

$$j_{ex}/j_{Ix} = (r_I/\ell)^2(\ell/\lambda_e)(m_e/m_I)^{\frac{1}{2}}\eta^{\frac{1}{2}} \simeq \phi^2(\ell/\lambda_e)(m_e/m_I)^{\frac{1}{2}}\eta^{\frac{1}{2}} \tag{9}$$

In Eq. (9), $\phi \equiv r_I/\ell$.

Our assumptions of E. M. region conditions require that $\phi > 1$, however, ϕ need not be large relative to 1 (i. e. $\phi \approx 3$).

By equating the joule heating, $j_{ex}E_x$, to the electronic heat transfer (under the assumption of long electronic mean free path), we can calculate approximate values for both the total wall losses and for the electron temperature, (i.e. hence, for η). The selection of a reasonable value for λ_e (based on mass continuity and the preceding assumptions) indicates that the value of j_{ex}/j_{Ix} should be less than 10^{-2}. On this basis, one also expects the fractional losses due to heat conduction to the walls to be much less than 10% and the electron temperature to be quite low.

The foregoing analysis suggests that the fractional electron leakage current will be proportional to n_e^2/B^2, or alternatively, that the electron current will be constant when the internal electric field varies as B^2/n_e^2.

For this idealized model, the ion current will approach a limiting value given by I_o where

$$I_o \equiv m \left(\frac{e}{m_I}\right) \tag{10}$$

Allowing for an arc voltage drop at the electrode sheath, V_{sheath}, the voltage current characteristics for this type of device should have the form given by Eqs. (11) and (12).

$$I = I_o + \left(\frac{n_e^2}{B^2}\right)\frac{V - V_{SHEATH}}{K} \tag{11}$$

$$V = V_{SHEATH} + (I - I_o)\frac{K B^2}{n_e^2} \tag{12}$$

The origin of the term in n_e^2/B^2 is readily apparent from inspection of Eq. (5).

D) Electron Leakage Currents - Anomalous Diffusion (Bohm) Case - In addition to mathematical simplifications, the preceding analysis has overlooked a number of potentially significant factors including effects associated with the spacial distribution of the ion production process, sheath effects, and effects associated with the reverse leakage of electrons in the region of weak magnetic field near the central axis of the cusp experiment. A much more fundamental question, however, centers around the validity of the classical theory for the diffusion of electrons across magnetic field lines.

According to the classical theory, the transverse electron current should vary according to the following relation:

$$j_{ex} \doteq \frac{E_x \sigma_o}{1 + (\omega_e \tau_e)^2} \approx \frac{E_x m_e}{B^2}\left(\frac{n_e}{T}\right) \propto \frac{E}{T^{3/2}}\left(\frac{n_e}{B}\right)^2 \tag{5}$$

Bohm and others[14-18] have suggested an alternative formula which presupposes turbulence in the plasma as a source of increased electron diffusion. According to this formula the electron current should vary as

$$j_{ex} \doteq \frac{E_x \sigma_o \propto}{(\omega_e \tau_e)} \doteq E_x\, e \left(\frac{n_e}{B}\right) \propto \tag{13}$$

where $\propto$ is a numerical quantity ($\approx 1/10$) which measures the average frequency of electron collisions with significant density fluctuations. Bohm[14] proposed a value of .06 for $\propto$ while Spitzer[15] has established an experimental fit with a value of 0.21. Recently, Yoshikawa and Rose[17] have discussed this phenomenon in a paper which established reasonable experimental fit for values of $\propto$ between 0.03 and 0.06.

The significant point about this phenomenon is that it proceeds at a rate proportional to n_e/B rather than to n_e^2/B^2. Furthermore, this type of diffusion should be relatively independent of electron temperature. Finally for $\omega_e \tau_e > 1/\propto$ (which is certainly the case of interest), the occurrence of this type of diffusion will greatly enhance the electron leakage currents.

The observation that

$$j_{ex}/_{BOHM} = (\omega_e \tau_e \propto)\, j_{ex}/_{CLASSICAL} \tag{14}$$

indicates that the equivalent formula to Eq. (8) is easily written for the case of Bohm type diffusion.

$$\frac{j_{ex}}{j_{Ix}}\Big/_B = \left(\frac{\lambda_I}{\ell}\right) \propto = \phi \propto \tag{15}$$

Assuming that $\phi \approx 3$, and $\propto = 1/15$, we obtain

$$\frac{j_{ex}}{j_{Ix}}\Big/_B = \frac{1}{5} \tag{16}$$

This number is a great deal larger than that predicted by the classical theory but not large enough to rule out the feasibility of this type of plasma accelerator. Further analysis along lines similar to those previously utilized for the classical case indicates that the electron temperature will be of the order of a few percent of the ion energy, but that in this case the energy losses associated with ions striking the wall because of expansion due to electron pressure may be serious (i.e., of order 1).

III. Experiments

On the basis of the preceding theoretical concepts, several steady state direct current E.M. region plasma accelerator experiments are being conducted. The initial experiments at the Avco-Everett Research Laboratory were conducted in argon with a cusp type geometry (see Fig. 1). Experiments are currently under way at AERL utilizing the geometrical configuration illustrated in Fig. 2. The experiments at United Aircraft Corporation were also conducted in argon with an experimental geometry similar to, but somewhat smaller than, that indicated in Fig. 2. The United Aircraft experiments did not contain the ionizer filament illustrated in Fig. 2 of the current AERL experiments and, therefore, made no provision for ionization other than the normal collision mechanism resulting from the axial leakage of electrons. In all of these devices it is intended that the axial mobility of electrons will be sufficiently restricted by the magnetic fields to permit the plasma to sustain a significant voltage associated with the electric fields necessary to accelerate the ions as current carriers. Electrons produced by ionization near the anode are carried to the exit through an external electrical circuit and there emitted from a hot filament in order to satisfy the requirements for obtaining an electrically neutral plasma in the exit beam.

A) <u>D.C. Cusp Experiments</u> - In the AERL D.C. cusp experiments (see Fig. 1) it was found that the reverse leakage of electrons along the central axis was sufficient to produce a 50% fractional ionization of the incoming flux of argon atoms. This information was obtained by integrating the total ion current flux as measured with a biased double Langmuir probe. The ion densities were estimated to be about 10^{12} particles per cm^3 on the basis of the Langmuir probe studies. Measurements were made with a negatively biased Langmuir probe, oriented in such a way as to collect circumferentially circulating ion currents. These measurements indicated that in the region around the radial cusp points, the ions had a circulating velocity in the $\vec{E} \times \vec{B}$ direction in excess of their thermal velocity. This conclusion is based on the observation that the ion collection current in the + $(\vec{E} \times \vec{B})$ direction exceeded the ion collection current in the - $(\vec{E} \times \vec{B})$ circumferential direction by a factor of approximately 5. This data is consistent with other Langmuir probe measurements which indicate that the local electric field in this region exceeds 20 volts per cm.

Direct force measurements utilizing the previously described scale and thrust plate arrangement indicated the presence of a plasma momentum flow within the cusps. Typical momentum measurements are shown in Fig. 7. Figure 7 is a plot showing the mean specific impulse as a function of the mean radial magnetic flux density at a radial cusp point. The dotted line displays the corresponding ratios of the ion gyro radius to an appropriately weighted characteristic length for the magnetic cusp configuration. Too much significance should not be attached to the absolute value of the quantity R_I/R in view of the fact that R_I/R has a divergent singularity on the axis. Most of the experimental data from the AERL experiments, including that shown in Fig. 7, was obtained with the total current I equal to twice the theoretical ion current I_o. The predominant feature of Fig. 7 is the nearly linear dependence of specific impulse upon magnetic field strength for moderate magnetic fields. The total voltage across the experiment also includes a sheath potential. The measured specific impulses correlated most closely with the increased voltages associated with the presence of the magnetic fields. The experiments at larger magnetic field strengths were prompted by the observation that the specific impulses observed at low magnetic field strengths corresponded to rather inadequate velocities. The apparent saturation in the observable specific impulse at large magnetic flux densities is probably associated with the parameter R_I/R. Unfortunately, the use of stronger magnetic fields to produce a greater specific impulse produced difficulties in the detachment of the plasma from the magnetic field at the exit. This difficulty was partially circumvented by shaping the magnetic field at the exit in such a way as to provide a more gradual decrease in the field strength (i.e., a magnetic nozzle).

Another feature of the experiments utilizing the larger magnetic field strengths was the appearance of excessive localized wall heating at the radial cusp points. This heating was sufficient to severely damage the outer quartz cylinder (see Fig. 8).

At high values of magnetic field strength, a large amplitude oscillation appeared in the anode to cathode voltage (see Fig. 10). The frequency of these oscillations corresponded roughly to 100 kc. This frequency did not appear to be coupled to any resonance elements in the associated circuitry. At very high values of magnetic field strength, the amplitude of these oscillations exceeded several hundred volts.

The lower curve in Fig. 9 illustrates the experimentally measured plasma voltages as a function of the maximum magnetic field strength. On the basis of this cusp experiment, it is not possible to draw any fundamental conclusions concerning the mechanisms controlling the diffusion of electrons across magnetic field lines. This difficulty is due to the presence of a null point in the radial magnetic field along the axis providing an alternative unevaluated leakage path.

B) <u>D. C. Plugged Cusp Experiments</u> - A modified experiment was performed in order to separate electron leakage arising as a consequence of the null point in the radial magnetic field from electron leakage associated with diffusion of electrons across magnetic field lines. In this modified experiment, plasma was excluded from the central core of the D. C. cusp accelerator by the insertion of a full length 2.75 cm diameter quartz insulating plug. This geometrical arrangement is illustrated by the inset drawing accompanying the upper curve in Fig. 9. This modification greatly reduced the backstreaming of electrons as indicated by the striking change in the slope of the curves relating total voltage to magnetic field strength. Indeed, the electron current was inhibited to the extent that serious difficulties were encountered in starting the discharge and maintaining adequate ionization. In addition, the spectral distribution of the emitted light was indicative of a lower electron temperature. The characteristics of the plug discharge were very sensitive to the geometrical location of the plug on the axis of the magnetic field. Moving the plug off of the axis made it possible to initiate the discharge with relative ease. On the basis of these observations, it was concluded that most of the backstreaming of electrons observed in the E. M. region D. C. cusp experiment was occurring in the central region of the discharge where the radial magnetic field vanished and that the effects of the plug on the voltage characteristics of this device were not primarily associated with the increased wall area. Unfortunately, measurements of the momentum flow within the plasma indicated some reduction in the net specific impulse under conditions corresponding to an increased total voltage and hence, increased total power input. This reduction was in part attributed to the increased wall area, but largely to the decreased ionization efficiency. Typical voltage current characteristics for this device are shown in Fig. 11.

C) <u>United Aircraft Experiments</u>[9,10,19] - As previously mentioned, the experiments of Lary, Meyerand, and Salz were conducted with argon in a geometry similar to, but somewhat smaller than, that indicated in Fig. 2. Since their experiments did not contain an ionizer, it was necessary to rely on the internal dissipation resulting from the axial leakage of electrons for the production of ionization. Their accelerator length was 10 cm, but the annular spacing available to the discharge was only 2 cm. Magnetic field strengths varied between 30 and 200 gauss while electric field strengths, as measured with a floating Langmuir probe, varied between 5 and 100 volts per cm. The mass flow rates were not directly measured, however, measurements with a biased double Langmuir probe indicated the presence of ion current densities in the range of 1-5 ma/cm^2. On the basis of this information, the total integrated ion currents were calculated to be between .05 and .25 amps. The total currents in the external circuit, including electron leakage currents, were of the order of 1 amp. These data suggest that the ion densities were in the range around 10^{10} particles/cm^3.

Comparison of the ion current densities with measurements of the flux of neutral particles indicated that approximately 5% of the incoming argon atoms were ionized. Presumably, this reduction in ionization efficiency relative to the AVCO experiments was a consequence of the lower particle densities and of the absence of any electron leakage along a null path on the axis (see Sec. III B). Probe measurements indicated the presence of an electron temperature the order of a few volts.

The most predominant features of the United Aircraft experiments were:

1) An electron leakage current across the magnetic field lines which exceeded that anticipated on the basis of the classical theory for electron diffusion by as much as a factor of 100.

2) Internal voltage gradients perpendicular to magnetic field lines which exhibited a linear rather than a quadratic dependence upon the magnetic field strength.

3) The presence of large amplitude coherent electric field oscillations in the 10 kc to 100 kc range with a frequency proportional to the magnetic field strength.

IV. Comparison of Theory with Experiments

Section II, C and D showed the importance of the electron diffusion rate in determining the operation of these devices. The anomalous diffusion formula (Eq. 13) predicts an electron current which is of the order of $\omega_e \tau_e$ times the electron current predicted by the classical theory (Eq. 5). The electron currents measured in all the devices that are described above are 10^2 to 10^3 times the currents predicted by classical diffusion theory. The currents are of the order of those predicted by the Bohm formula. In both the plugged cusp experiment (Fig. 9) and the United Aircraft experiment, the voltage across the discharge is proportional to B rather than B^2. The best fit for the slope of the upper curve in Fig. 9 is obtained by taking $\propto = 0.3$ in Eq. (13). This result can be said to agree with those of Spitzer,and Yoshikawa and Rose since the geometry in these experiments is too complicated to determine $\propto$ within a factor of 2.

The turbulence that is responsible for the enhanced diffusion that is observed in these experiments is not well understood. Voltage oscillations that are observed in this type of discharge may be associated with the turbulence. In the United Aircraft experiments, the oscillations have a frequency between 10 and 100 kc. Their observed frequency was proportional to magnetic field strength but did not correspond to the electron, ion, or mixed cyclotron frequencies. In the AERL experiments, in which the magnetic field is 100 times stronger than the field in the United Aircraft experiments, the oscillation frequency is about 100 kc. The dependence of the oscillation amplitude on magnetic field strength is shown in Fig. 10. At high current densities, Yoshikawa and Rose also observe voltage oscillations in this frequency range. The only combination of plasma parameters which corresponds to this frequency in all experiments seems to be the ratio of the sound speed in the plasma to the plasma dimension. Further theoretical and experimental investigation is needed to justify this conjecture and to determine the relation of these oscillations to the diffusion mechanism.

V. Summary and Conclusions

E. M. region D. C. plasma accelerators have a number of significant potential engineering advantages. These include:

1) Freedom from the space charge limitations of conventional ion rockets.

2) Magnetic containment possibilities.

3) High acceleration voltages which depend only upon the specific impulse rather than upon the instantaneous power level, thereby minimizing arc voltage drop problems.

4) A readily variable specific impulse and power level.

5) Extreme simplicity in the associated electrical circuitry.

6) Convenient physical size together with moderate power levels, electrostatic voltage gradients, magnetic field strengths, and heat transfer rates.

The experiments described in this paper establish the basic soundness of the E. M. region mechanism for the electrostatic acceleration of low density plasma by momentum transfer through magnetic fields. These experiments further indicate that electron leakage currents which are of sufficient magnitude to account for the necessary ionization mechanism definitely do not obey the classical diffusion formula and show fairly good agreement with the anomalous diffusion formula proposed by Bohm. This may be a serious limitation on the overall performance of this type of device.

The necessity for the production of ionization by means of electron leakage currents probably precludes the possibility of searching for a domain of operation in which the electron currents are diminished. By establishing a physical separation between the ionization and the acceleration phases of this device, it should be possible to search for a more quiescent domain of operation in which the anomalous electron diffusion associated with density fluctuations may be significantly reduced. In addition, such a separation would greatly simplify the theoretical analysis of the experiments.

On this basis, we are now investigating an annular E. M. region D. C. accelerator which eliminates the necessity for electron leakage currents as a source of ionization.

In this experiment, schematically indicated in Fig. 2, the ionization is produced by a P. I. G. type discharge occurring between the ionizer filament and the anode. The ion acceleration takes place in an electrically neutral region immediately below. The filament at the exit need only serve to release the electrons which are necessary to neutralize the outgoing plasma. Unfortunately, sufficient data is not yet available to draw any conclusions on the basis of experiments as yet performed with this device.

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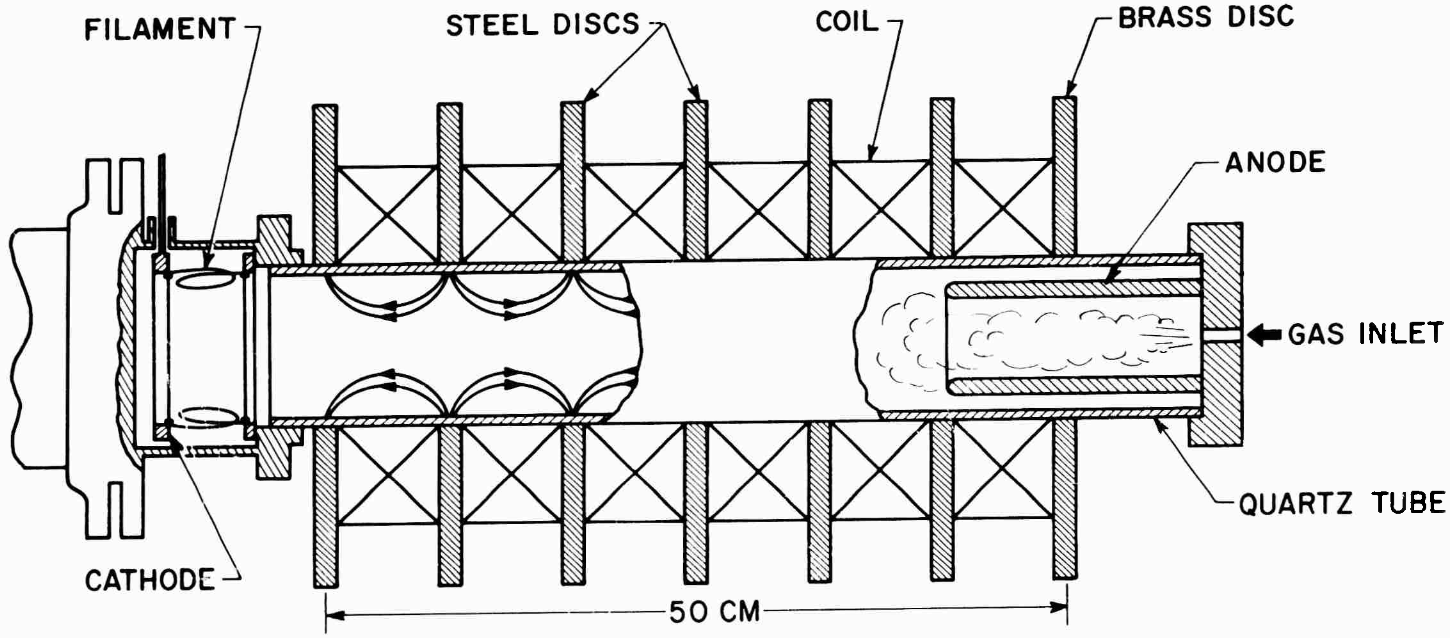


Fig. 1 Schematic diagram of the E. M. region D. C. cusp plasma accelerator. The coils and steel discs combine to produce a cusp type magnetic field configuration within the quartz tube. The gas inlet also serves as the anode. A D. C. generator is connected between the anode and filament to supply the drive current. The plasma exhausts into a vacuum at the left.

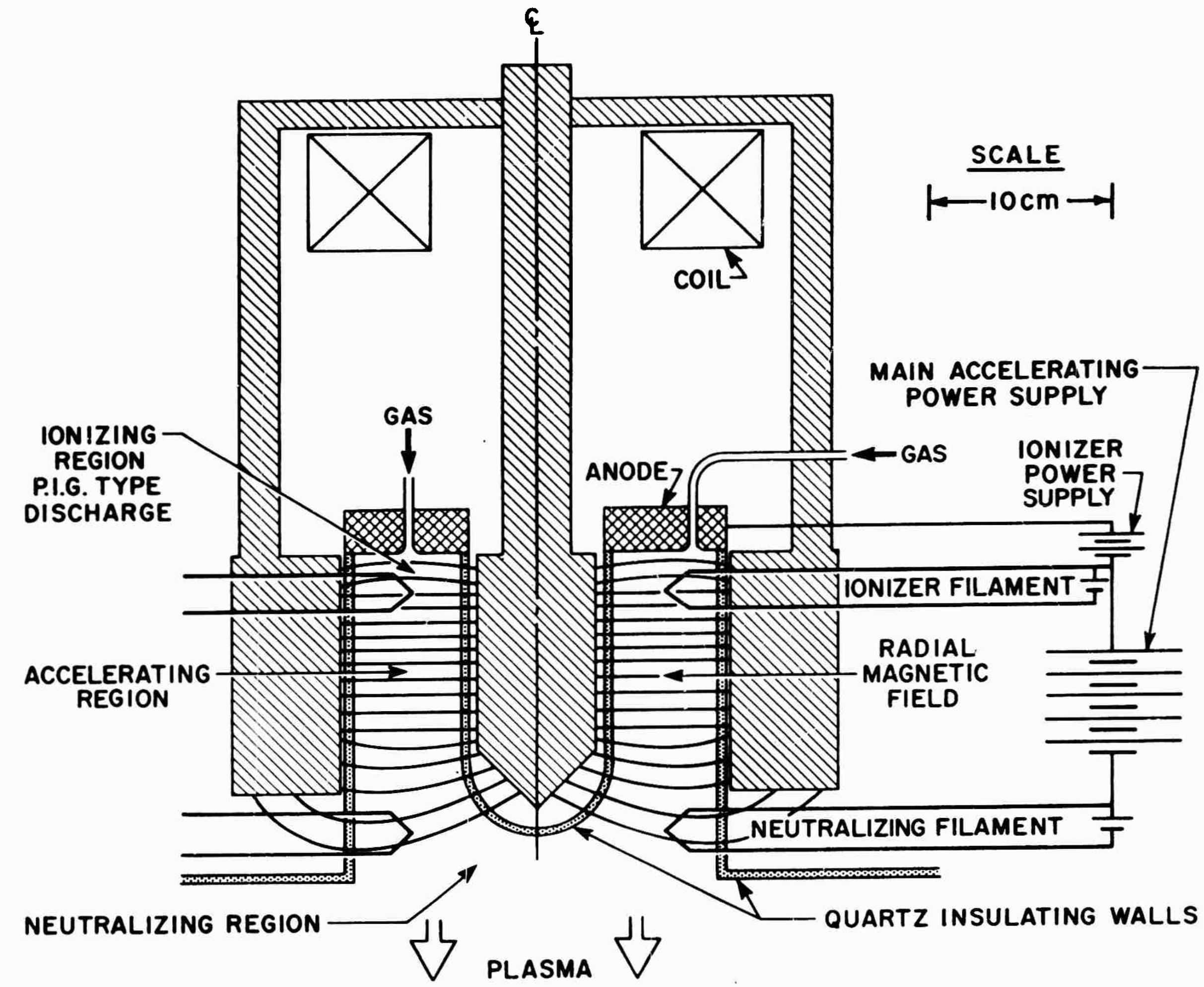
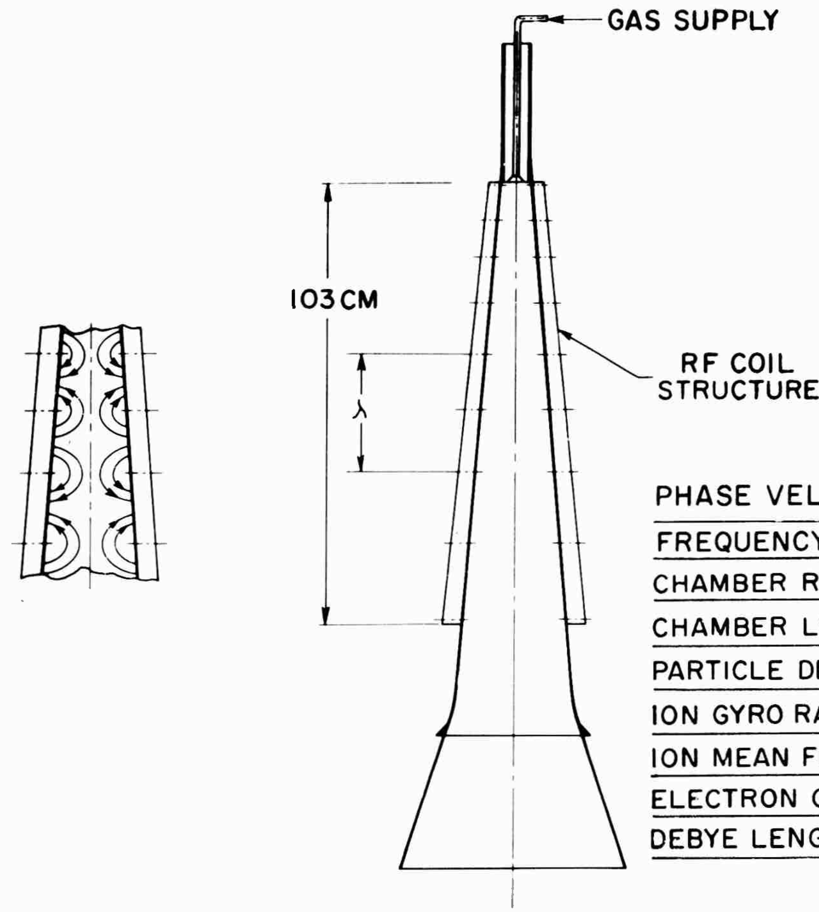


Fig. 2 Schematic diagram illustrating the basic concept of the annular two-stage E. M. region D. C. plasma accelerator currently under investigation at the Avco-Everett Research Laboratory. The ionization is produced by a P. I. G. type discharge occurring between the ionizer filament and the anode. The primary ion acceleration takes place in the accelerating region containing a radial magnetic field of moderate strength and an axial electric field. The filament at the exit serves to release electrons which neutralize the outgoing plasma and maintain the axial voltage gradient.



PHASE VELOCITY	V_ϕ	1 — 4	CM/μ SEC
FREQUENCY		115	KC
CHAMBER RADIUS	R	3 — 10	CM
CHAMBER LENGTH	ℓ	120	CM
PARTICLE DENSITY	n	10^{11} — 10^{12}	CM^3
ION GYRO RADIUS	r_I	10 — 100	CM
ION MEAN FREE PATH	λ_I	100 — 1000	CM
ELECTRON GYRO RADIUS	r_e	0.1 — 1	CM
DEBYE LENGTH	h	< 0.01	CM

Fig. 3 Schematic diagram of the E. M. region RF traveling wave plasma accelerator. At the left is a sketch of the RF magnetic field structure known as a cusp configuration. The short dashed lines indicate the half-wave repeat length of the coil structure. These field configurations must be thought of as moving continuously down the channel at the local phase velocity. The attached Table lists a number of pertinent physical parameters for the device.

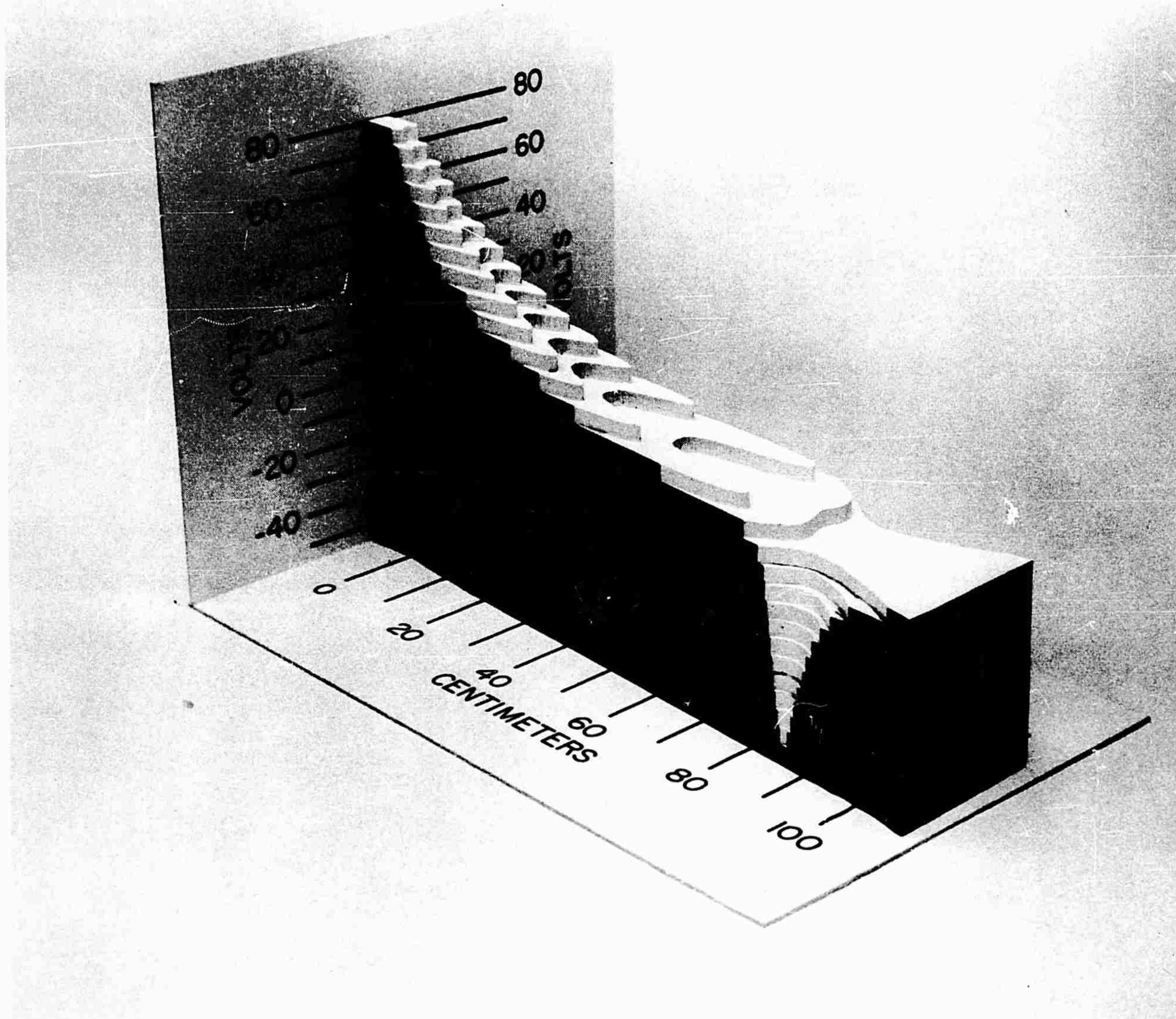


Fig. 4 Photograph of a contour model showing the over-all time averaged potential distribution within the E. M. region RF traveling wave accelerator. Both the axial accelerating fields and the radial fields which are responsible for providing the axial containment of ions are here evident.

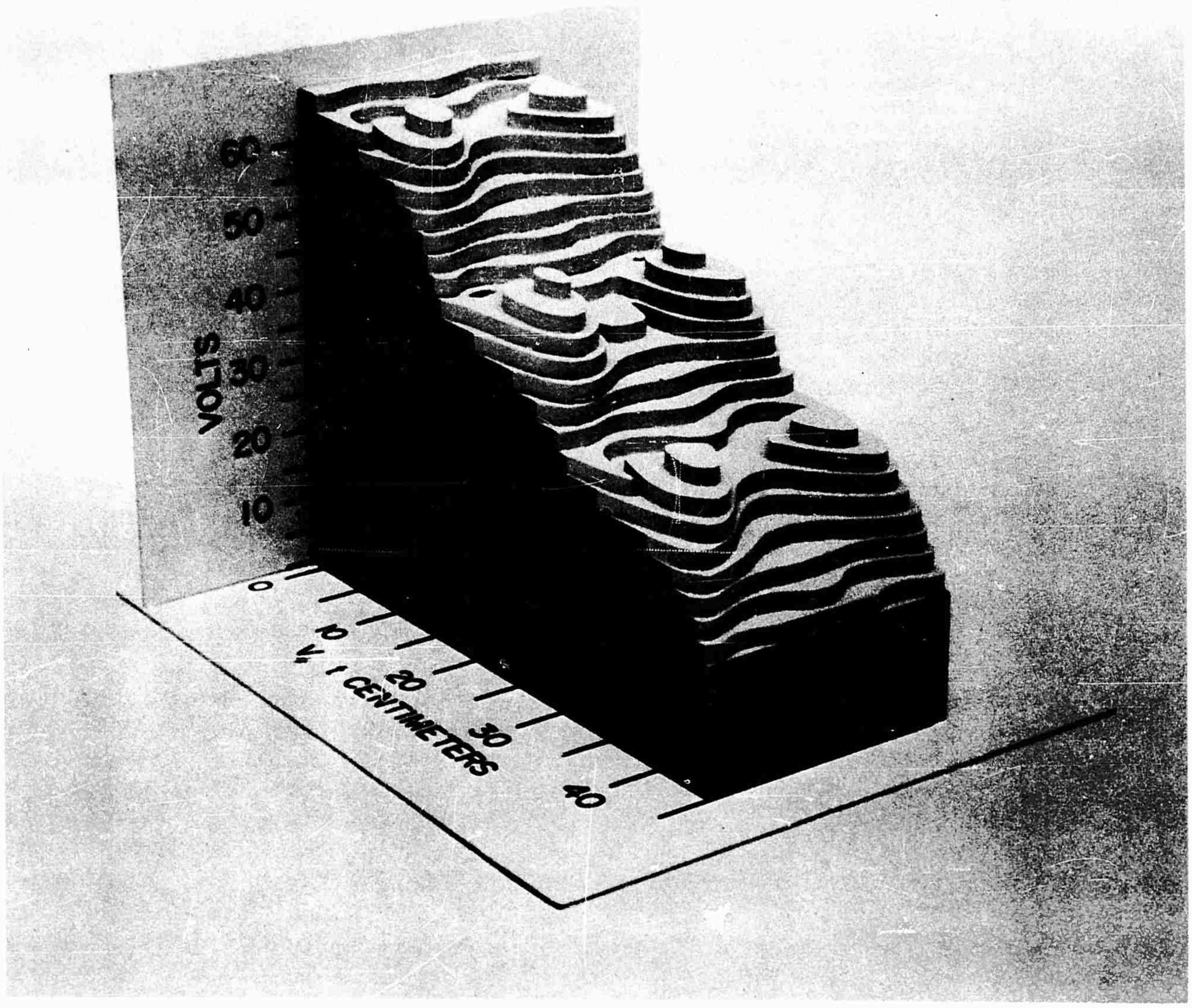


Fig. 5 Photograph of a contour model showing the instantaneous potential distributions within the E. M. region RF traveling wave accelerator as a function of radial and axial coordinates.

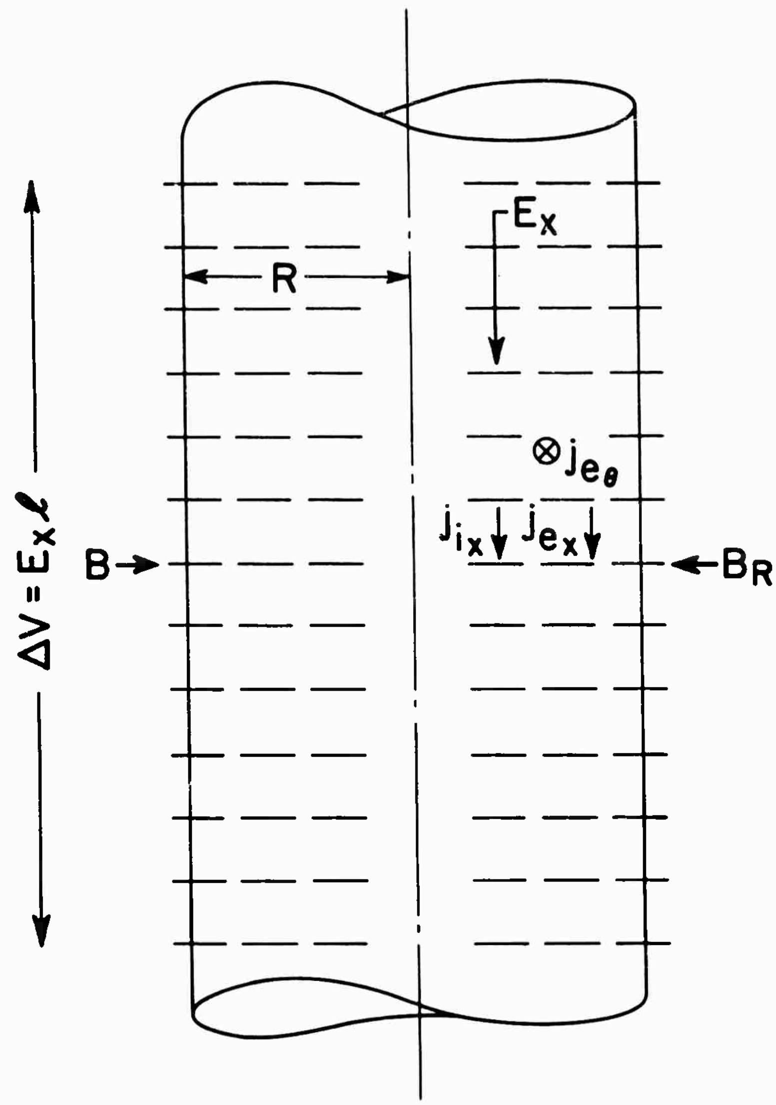


Fig. 6 Diagram illustrating the basic geometry utilized for theoretical calculations concerning the behavior of E. M. region D. C. plasma accelerators.

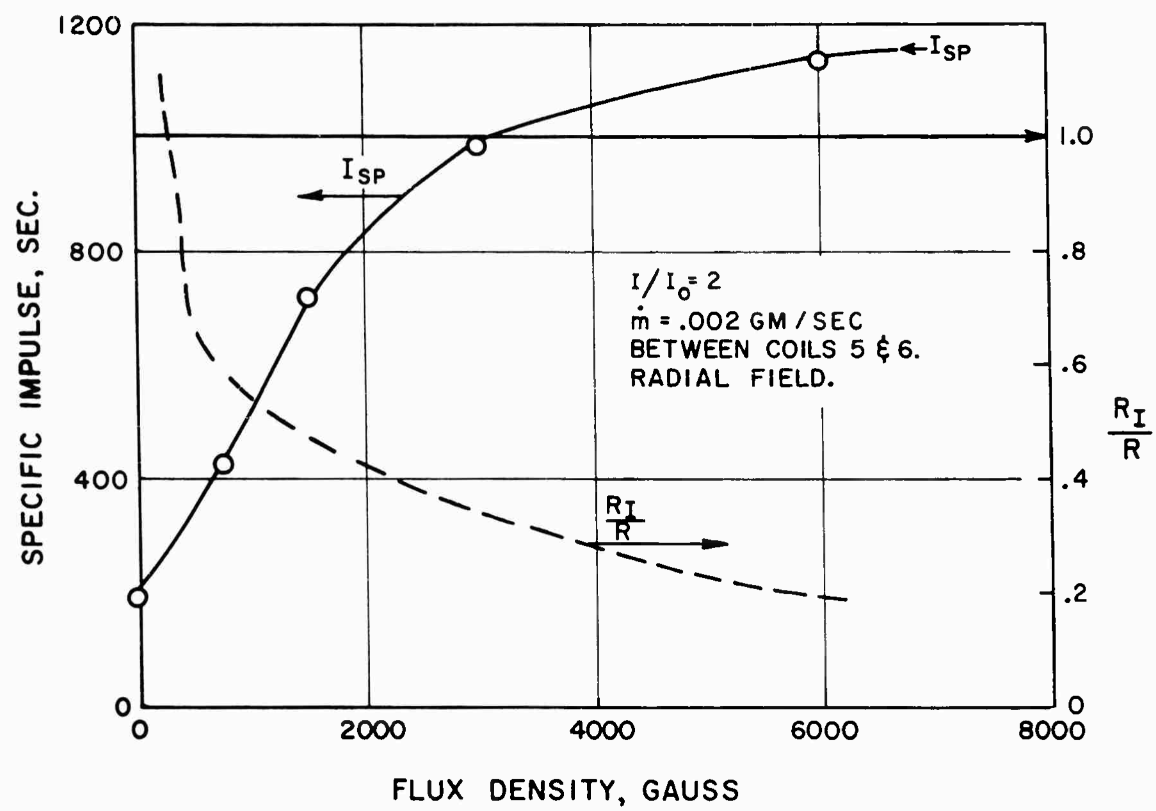


Fig. 7 Mean specific impulse within the E. M. region D. C. cusp accelerator as a function of radial magnetic field strength at the radial cusp points. The dotted line displays the corresponding ratio of the ion gyro radius to an appropriately weighted characteristic length. Too much significance should not be attached to the absolute value of the quantity R_I/R in view of the fact that R_I/R has a divergent singularity on the axis.

Fig. 8 Photograph illustrating wall damage at cusp points in the E. M. Region D. C. Cusp Accelerator Experiment. Interestingly enough, the narrow grooves cut into the tubing at the cusp points have a width which is comparable with the electron rather than with the ion gyro radii.

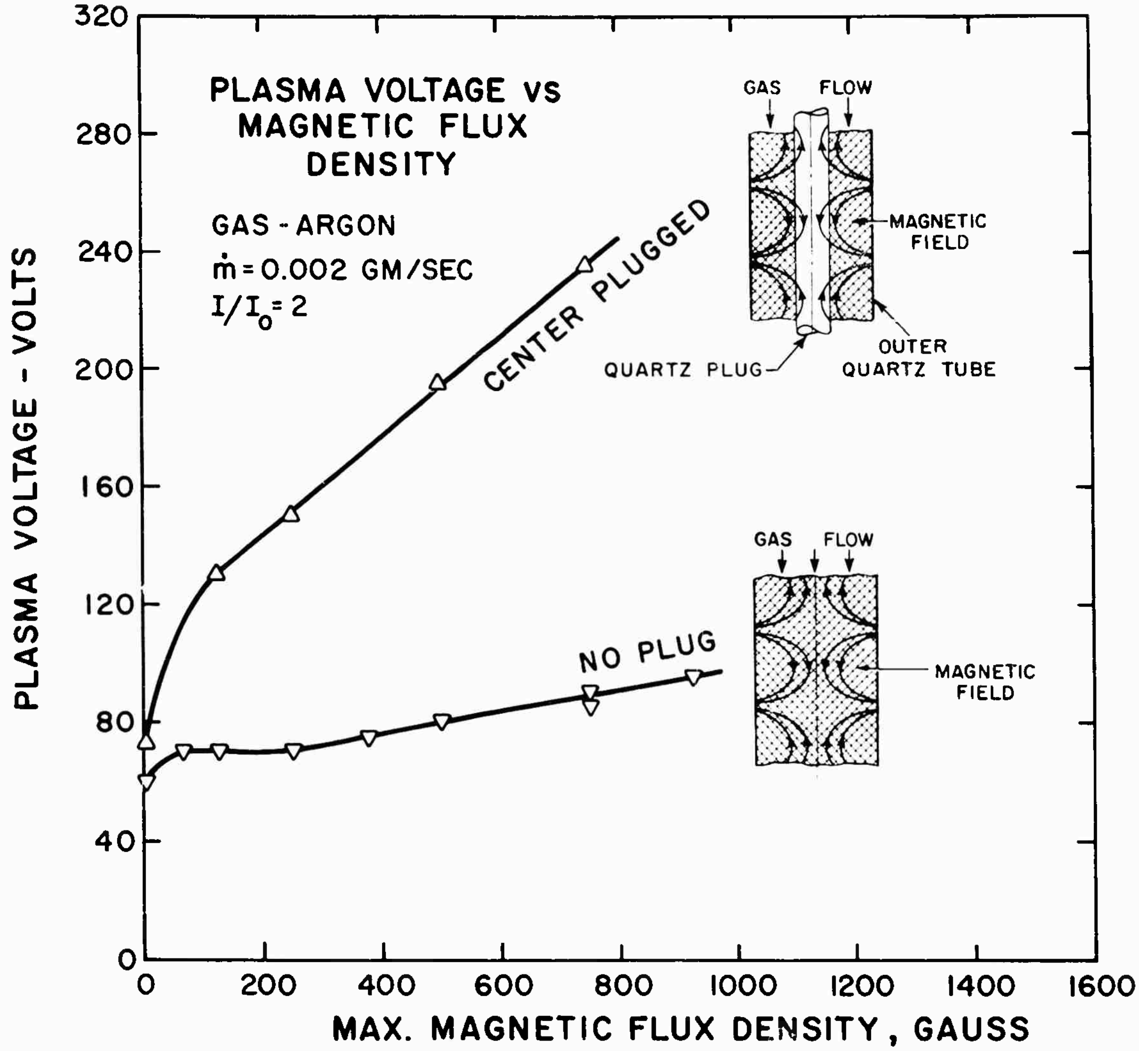


Fig. 9 Total discharge voltage versus maximum magnetic field strength within the E. M. region D. C. cusp accelerator for a total current equal to twice the theoretical ion current. The data for the lower curve was obtained with the straightforward cusp geometry indicated in the accompanying (lower) inset figure. The data for the upper curve was obtained with the plugged cusp geometry indicated in the accompanying (upper) inset figure.

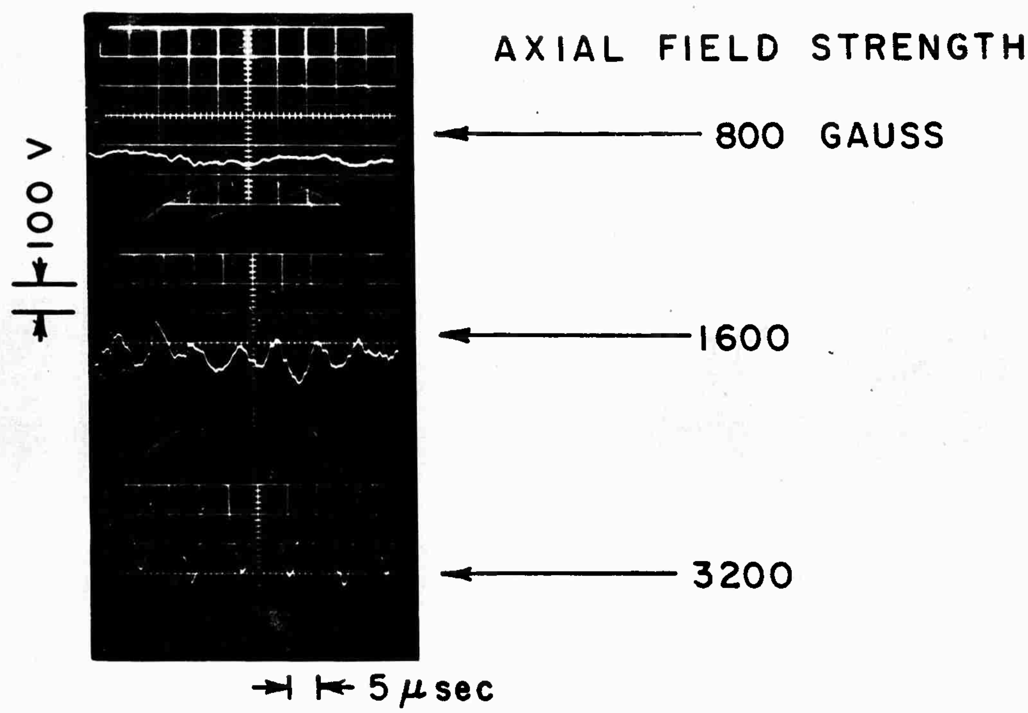


Fig. 10 Oscilloscope traces illustrating the magnitude and magnetic field strength dependence of oscillations observed in the anode to cathode voltage for the E. M. Region D. C. Cusp Experiment.

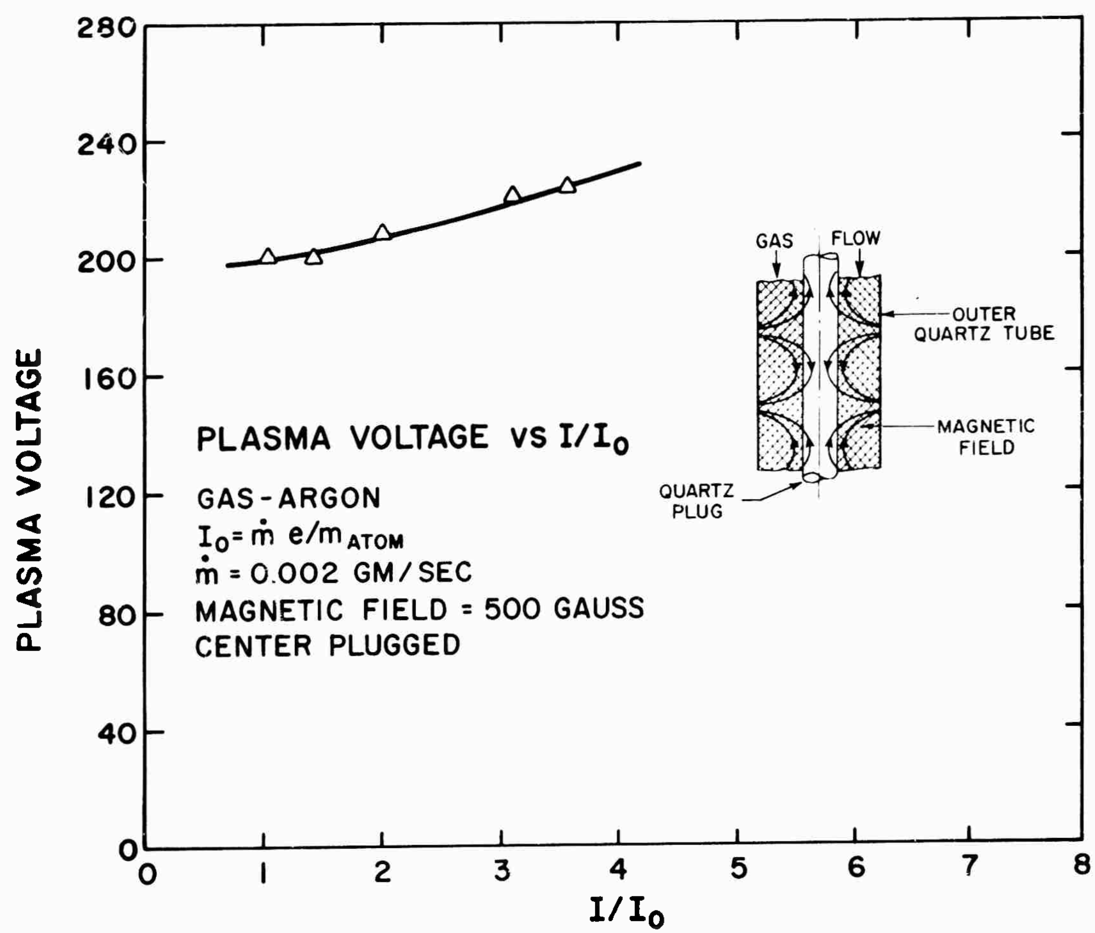


Fig. 11 Total discharge voltage versus the ratio of the discharge current to I_0, the theoretical ion current, for the plugged cusp experiment. I_0 is equal to 4.8 amps for this mass flow rate of .002 gm/sec. The plugged cusp geometry is illustrated by the inset drawing on the right.

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